Multi-Objective Path Planning for a Team of Unmanned Aerial Vehicles (UAVs) in a Dynamic and Uncertain Environment

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- Hierarchical Mission Planning Framework
- Multi-Objective Path Planning for UAVs
- Problem Formulation
- Simulation Results
- Conclusion
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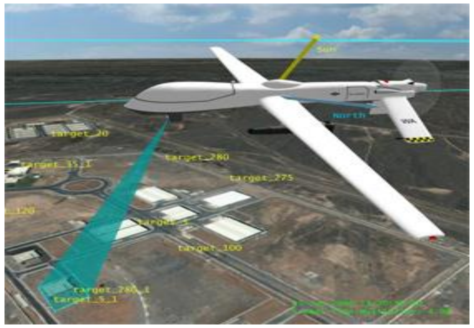
- References

Introduction: UAV Mission Planning

- UAVs have ***ultra long endurance*** and can accept ***high mission risk***; these attributes make them suitable for *dull*, *dirty,* and *dangerous* tasks in complex environments:



  - Military:
    - Intelligence, Surveillance & Reconnaissance (ISR)
    - Search and Rescue Operations (SAR)
    - Demining Operations

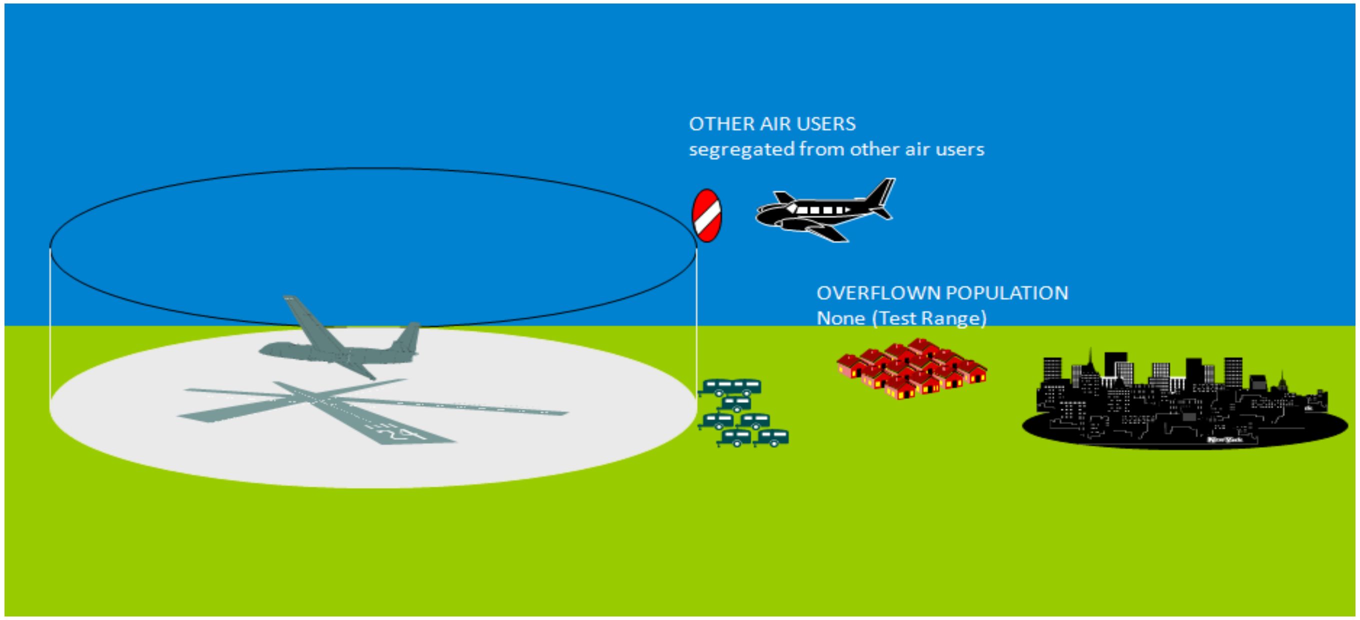
  - Security:
    - Border Patrol
    - Surveillance of Smuggling Operations
    - Interdiction Operations

  - Civil:
    - Disaster Management
    - Forest Fire Detection
    - Traffic Monitoring

- In the future, UAVs are expected to operate with a higher level of autonomy to carry out complex tasks, while efficiently coordinating with unmanned ground and unmanned underwater vehicles $\Rightarrow$ Need for systematic mission planning processes

Technical Challenges

- Lack of see and avoid capability :
  - May lead to mid-air collisions with manned vehicles
  - Restricts UAVs to operate in segregated regions in the airspace
  - Needs substantial human supervision
  - Limits operational flexibility

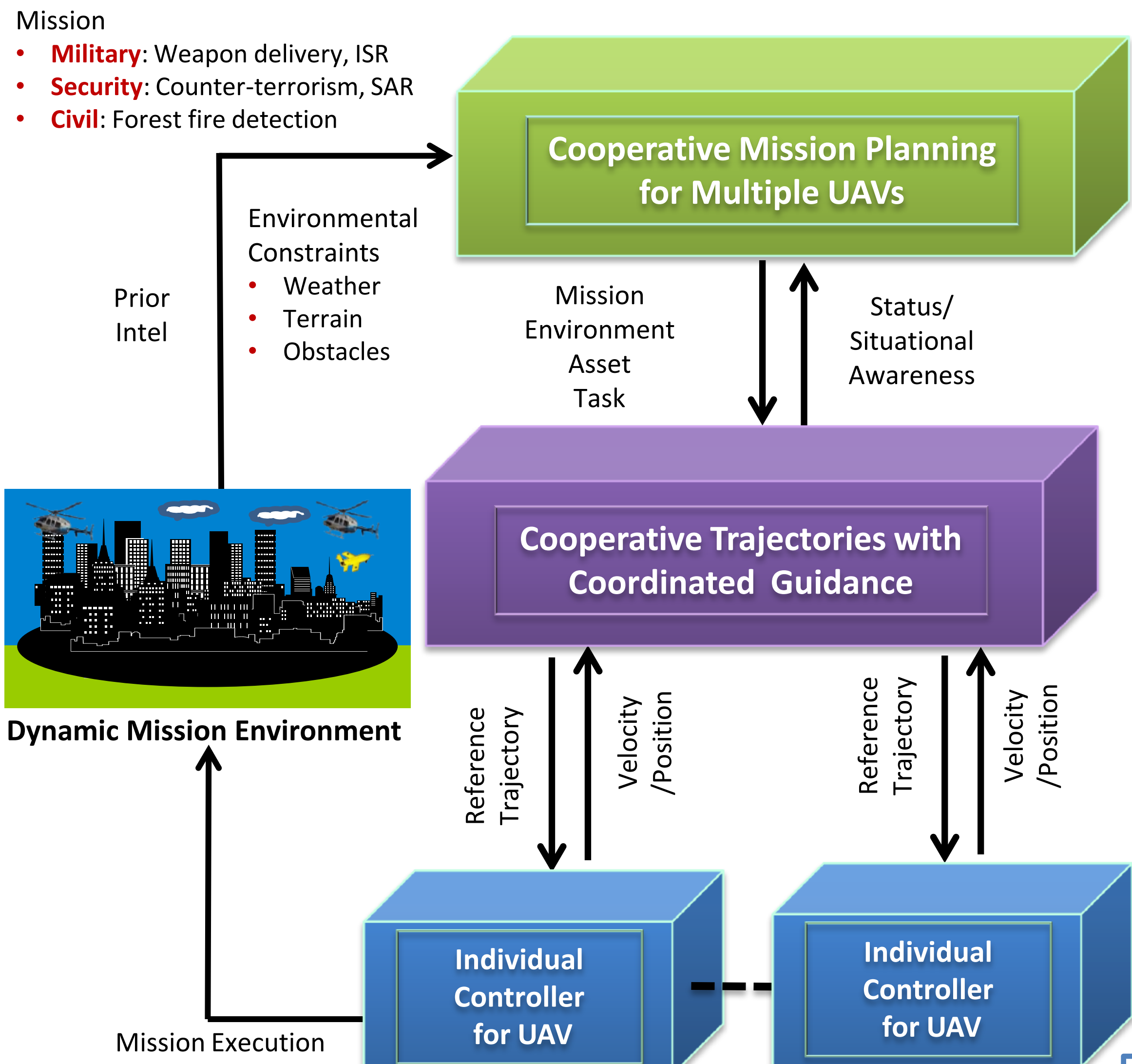


Flying UAV within national borders in controlled, segregated airspace over an unpopulated area

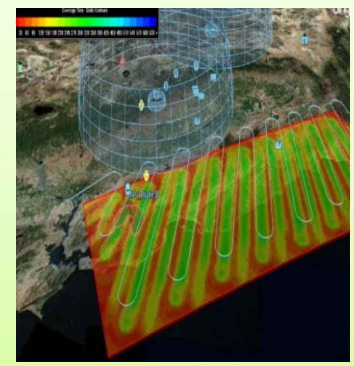
- Limited sensor ranges and payload capacity requires multiple UAVs to:
  - Work cooperatively
  - Expedite the mission execution
  - Reduce the possibility of mission failure

Hierarchical Architecture for UAV Mission Planning

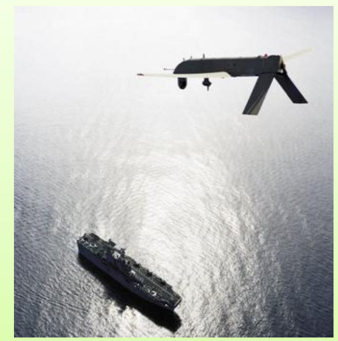
- Systematic mission planning structure for conducting complex tasks involving multiple UAVs



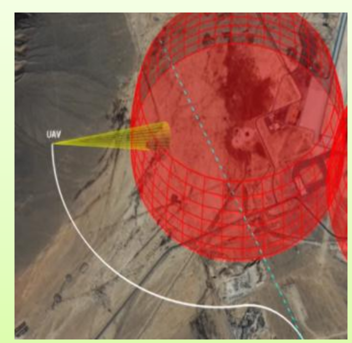
Dynamic Path Planning



Target Search & Tracking



Dynamic Task Assignment



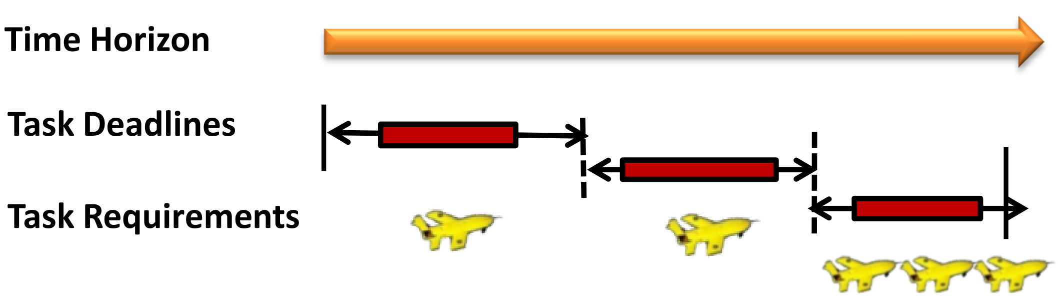
Formation Hold

Ref: http://www.agi.com/solutions/uav-and-aircraft-mission-software/Default.aspx

Multi-Objective Path Planning for UAVs

- **Objective**: *Coordinated* multi-objective path planning for a group of UAVs in a dynamic environment to carry out *time-critical mission tasks*:
  - Minimize mission risk (path cost, e.g., distance of UAV from obstacle)
  - Minimize task latencies

Mission Scenario

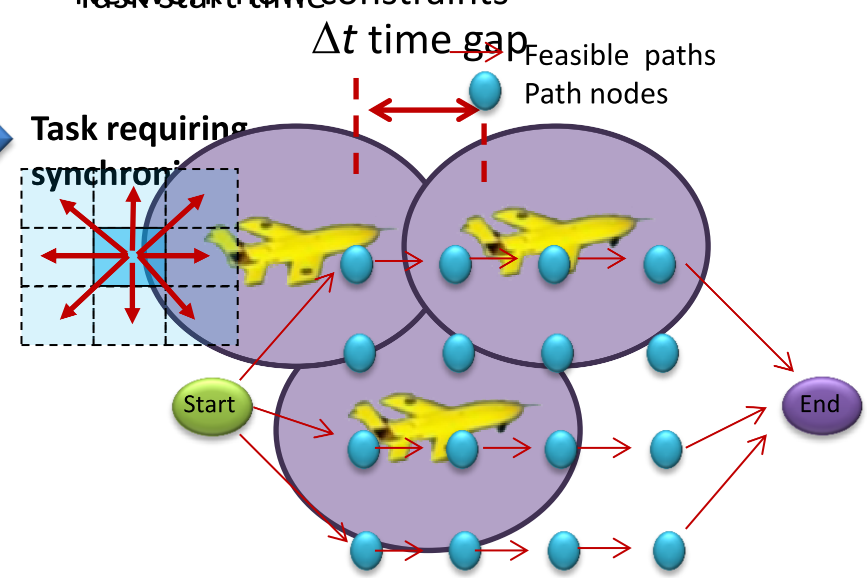


Given:

- Dynamic environment with static and dynamic obstacles, e.g., high rise buildings,,manned aircraft
- Task locations, deadlines, task requirements

Constraints:

- Deconfliction constraint
- Synchronization
- Network flow constraints
- Task start time



Introduction

Technical Challenges

Path Planning Framework

Objectives & Constraints

Results

UAV Path Planning Formulation

- Multi-Objective Mixed Integer Linear Programming (MILP) Problem:
  - *Objective I: Minimize cumulative path risk* - Time varying travel and usage cost

$$\text{Obj}_1 : \min_{x_{ijkt}} \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{(i,j)\in\Omega} r_{ijkt} x_{ijkt} \qquad (1)$$

$$x_{ijkt} = \begin{cases} 1, & \text{if UAV } k \text{ moves from cell } i \text{ to cell } j \text{ at time } t \\ 0, & \text{otherwise} \end{cases}$$

where T is the time horizon, K is the total number of UAVs and Ω is the set of accessible paths

r_{ijkt} is the path risk experienced by UAV k in moving from cell i to cell j at time t

  - *Objective II: Minimize task latency* - Delay in meeting the task deadline

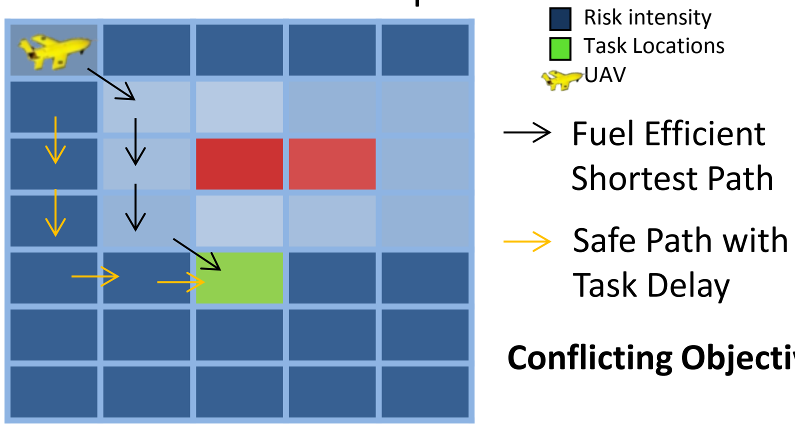
$$\text{Obj}_2 : \min \sum_{l=1}^{L} t_l^{latency}, \quad t_l^{latency} = \max(0, t_l^{start} + t_l^{process} - t_l^{deadline}) \qquad (2)$$

where

$t_l^{start}, t_l^{process}, t_l^{deadline}$ denote the start time, processing time and deadline for task l

L denotes the total number of tasks

Mission Area Risk Map



Conflicting Objectives

Multi-Objective MILP Problem Constraints

- *Network Flow Constraints*: Time-varying travel and usage cost

$$\sum_{t=1}^{T}\sum_{i\in Q(1,t)} x_{1ikt} = 1, \forall k \qquad 1(a)$$

$$\sum_{t=1}^{T}\sum_{i\in P(N,t)} x_{iNkt} = 1, \forall k \qquad 1(b)$$

$$\sum_{t=1}^{T}\sum_{j\in Q(i,t)} x_{ijkt} - \sum_{t=1}^{T}\sum_{j\in P(i,t)} x_{jikt} = 0, \ \forall k, \forall i \neq 1 \,\&\, i \neq N \qquad 1(c)$$

$$\sum_{t=1}^{\tilde{T}}\sum_{j\in Q(i,t)} x_{ijkt} \leq \sum_{t=1}^{\tilde{T}}\sum_{j\in P(i,t)} x_{jikt}, \forall k, \forall i \neq 1, \forall \tilde{T} < T \qquad 1(d)$$

where
x_{ijkt} : Path risk
k : UAV index
N : Total number of cells
T : Time horizon
$Q(i,t)$: Successor cells of i at time t
$P(i,t)$: Predecessor cells of i at time t

- *Task Execution Constraints*: Delay in meeting the task deadline

$$t_{kloc(l)}^{depart} \geq t_l^{start} + t_l^{process}, \ \forall l, \forall k \in \Psi_l^{asgn} \qquad 2(a)$$

$$t_l^{start} = \max_{k\in\Psi_l^{asgn}} t_{kloc(l)}^{arrive}, \forall l \qquad 2(b)$$

$$\sum_{j\in P(loc(l),t)} \sum_{k=1}^{K} x_{jloc(l)kt} \leq q_l, \ \forall l, \forall t \qquad 2(c)$$

where
$t_{kloc(l)}^{depart}$: Departure time of UAV k
$t_{kloc(l)}^{arrive}$: Arrival time of UAV k
Ψ_l^{asgn} : Set of assigned UAVs for task l
q_l : Maximum number of UAVs for task l
$loc(l)$: Location of task l

Multi-Objective MILP Problem Constraints

- *Collision Avoidance Constraints*: Ensures safe path by avoiding collision with obstacles

$$t_{k'i}^{arrive} - t_{ki}^{depart} \geq \Delta t - M\alpha_{kk'i} \;\; \forall i,k,k' \neq k \qquad 3(a)$$

$$t_{ki}^{arrive} - t_{k'i}^{depart} \geq \Delta t - M(1-\alpha_{kk'i}) \;\; \forall i,k,k' \neq k \qquad 3(b)$$

$$\alpha_{kk'i} \in \{0,1\}, \forall i,k,k' \neq k$$

where

M : Large number

$\alpha_{kk'i}$: Binary variable indicating when UAV k arrives after k'

Δt : Time gap

- *Arrival and Departure Constraints:* Tracks the execution status of tasks

$$t_{k1}^{arrive} = 0, \forall k \qquad 4(a)$$

$$t_{ki}^{depart} + t_{k}^{travel} x_{ijkt} \leq t_{kj}^{arrive} + M(1-x_{ijkt}), \forall k, \forall i, \forall j \neq 1, \forall t \qquad 4(b)$$

$$t_{ki}^{depart} \geq t_{ki}^{arrive}, \;\; \forall i \notin \{loc(l)\}, \forall k \qquad 4(c)$$

$$t_{ki}^{depart} \geq t_{ki}^{arrive}, \;\; \forall i \in \{loc(l)\}, \forall k \notin \Psi_{l}^{asgn} \qquad 4(d)$$

where

t_{ki}^{depart} : Departure time of UAV k from cell i

t_{k}^{travel} : Travel time of UAV k

t_{ki}^{arrive} : Arrival time of UAV k at cell i

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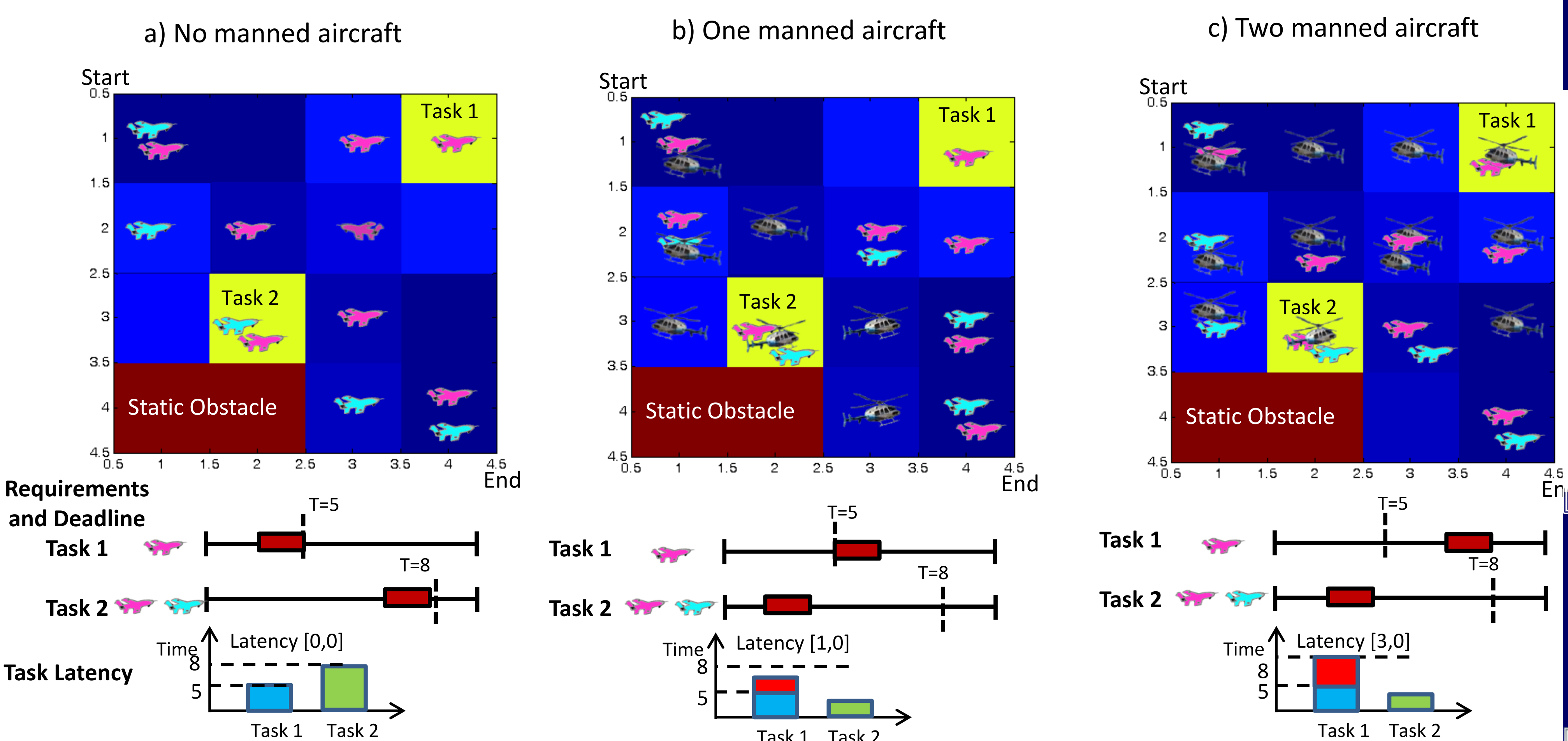
Results

UCONN

Multi-Objective UAV Path Planning Results

- **Solution**: Decomposed MILP solution approach:
  - **Phase I:** Minimize the path risk of each UAV given the estimated arrival time at each task location
  - **Phase II:** Minimize the task latency with respect to the arrival time of each UAV at each task location given the path in Phase I
- **Scenario I**: Coordinated path planning in different contexts



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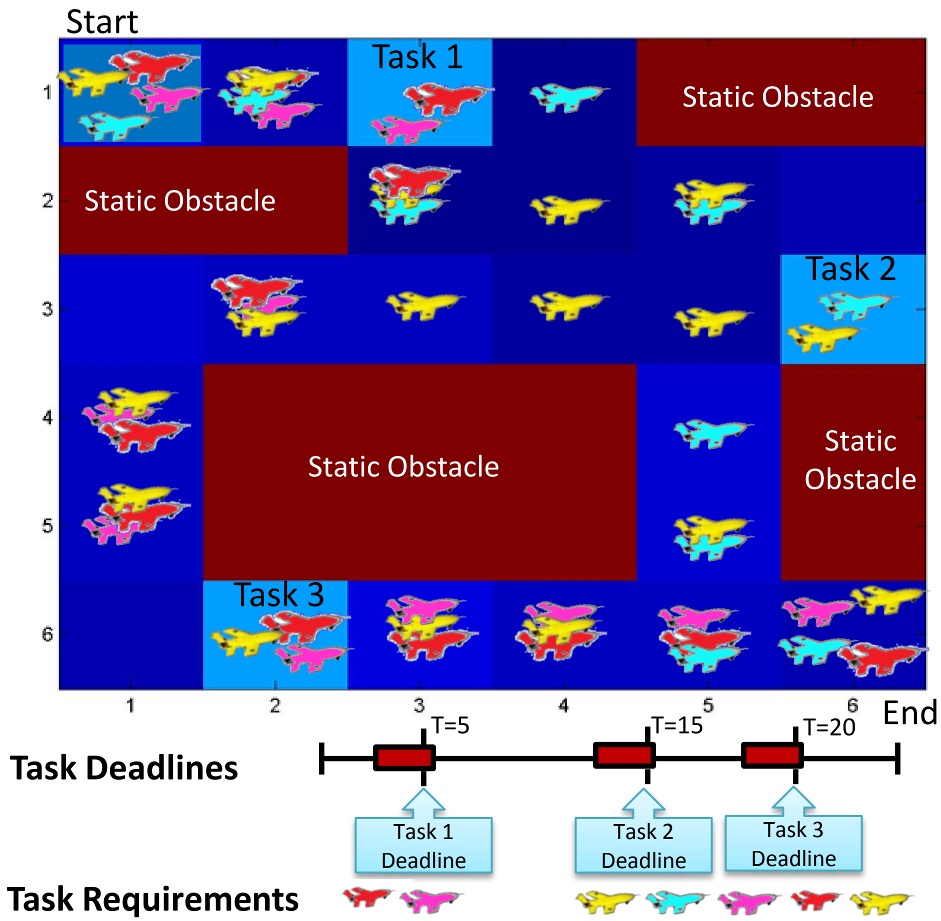
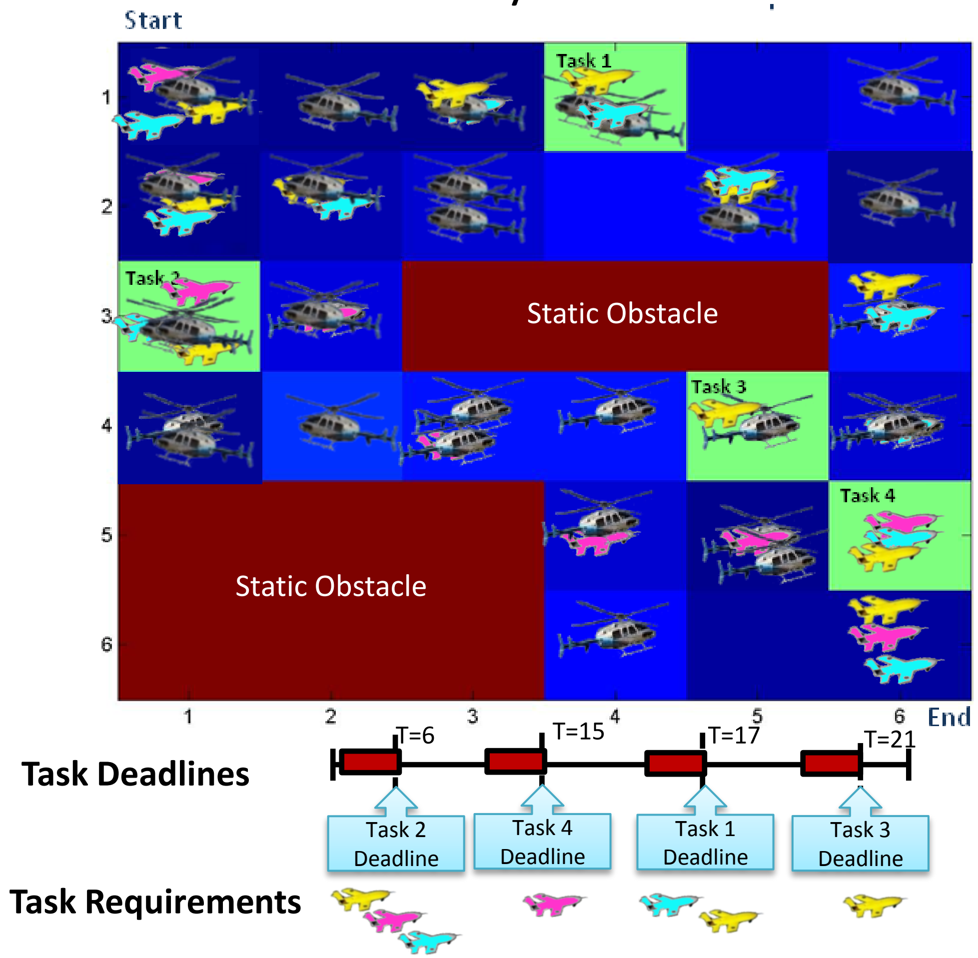
Multi-Objective UAV Path Planning Results

- **Scenario II**: Coordinated path planning around static obstacles



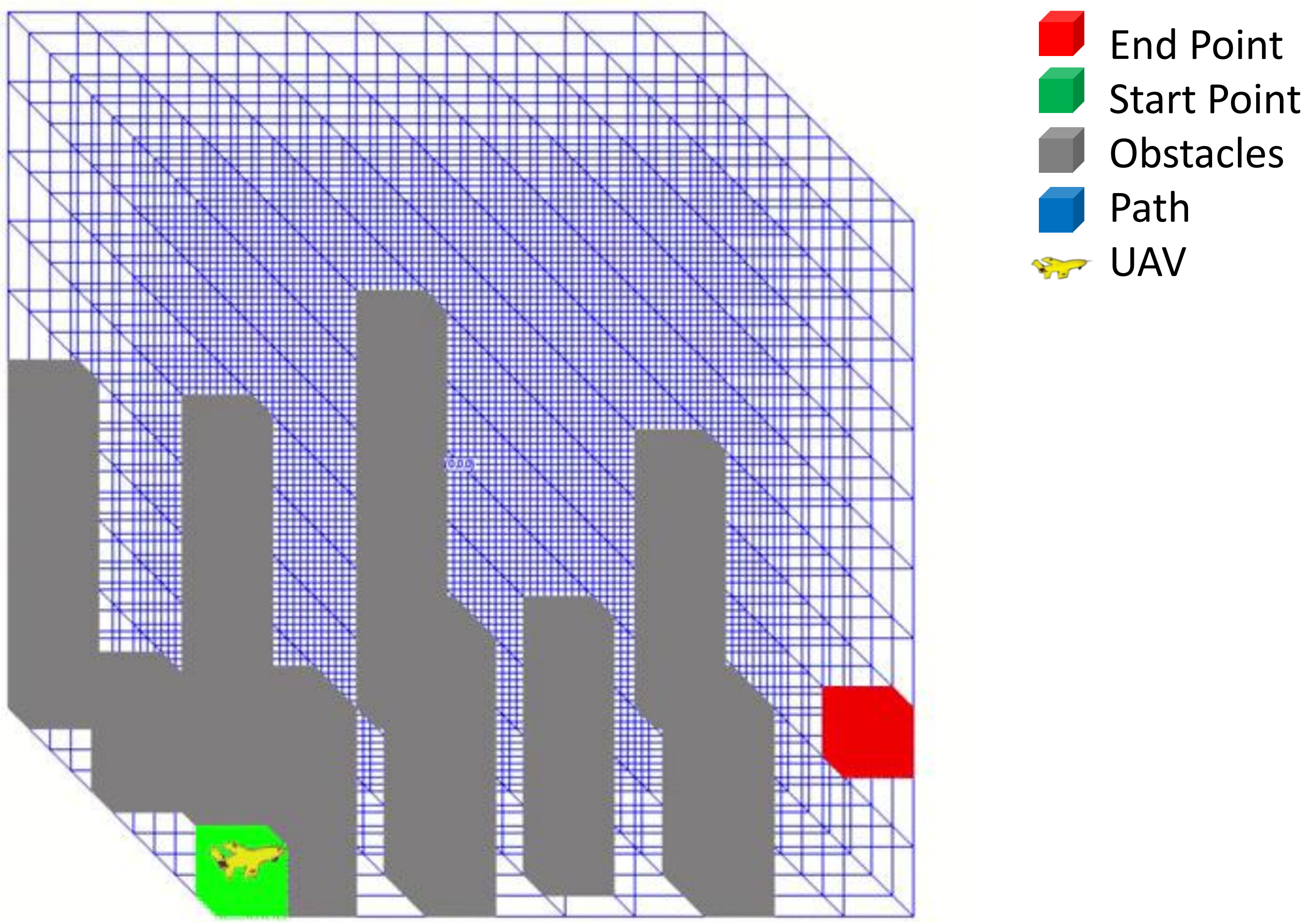
- **Scenario III**: Coordinated path planning around static and dynamic obstacles



- **Scenario I**: An increase in the number of manned aircraft delays the task processing time in order to guarantee safe trajectory planning within a confined mission area
- **Scenario II & III**: Mission tasks are completed on time in a large environment with static and dynamic obstacles

Python Implementation of 3D A* Algorithm

- Given:
  - Mission: Path planning
  - Environment: 3D mission space
  - Asset: UAV
  - Task: Plan path from start point to end point while avoiding static obstacles
- Future Work: 3D path planning for multiple UAVs within a dynamic environment



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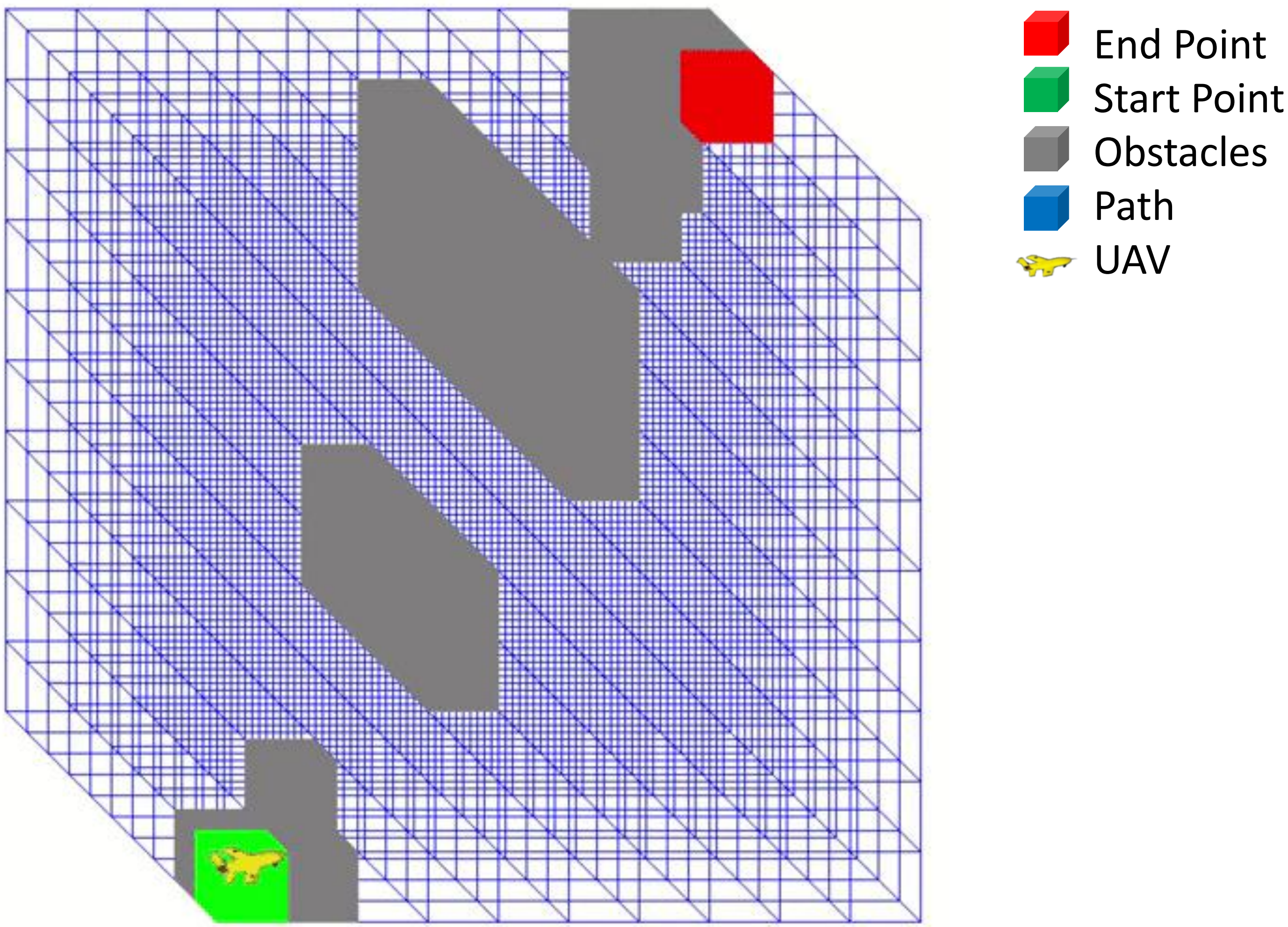

Conclusion

- Summary
  - UAVs are useful for dull, dirty, and dangerous military and civilian operations
  - A multi-objective UAV path planning problem was investigated for coordinated task execution in a dynamic environment including:
    - Mathematical formulation of the path planning problem
    - A two-phase algorithm to solve the resulting MILP problem
  - 3D A* algorithm was implemented in Python

- Future Work
  - Explore approximation techniques, such as ant colony system and genetic algorithms
  - Revise the current planning structure to a distributed setting
  - Explore 3D path planning and address the vertical collision avoidance problem
  - Incorporate pop-up threats and sudden UAV breakdown scenarios

Future UAV Mission Planning Challenges

Future UAV Mission Planning Challenges

- Provide capabilities more efficiently through *modularity and interoperability*
- Increase in autonomous *multi-platform control*
- More *survivable* with improved and *resilient communications* and security from tampering
- Efficient *manned and unmanned teaming to reduce the number of personnel* required to operate and maintain the systems
- *Consider realistic models* and incorporate/fuse data from different sources

UAV Mission Planning Objectives

- *Dynamic coordination* of multiple unmanned vehicles operating on ground, air, and water
- Develop efficient *algorithms to mimic human-like behavior* in unmanned aerial vehicles for proactive decision support
- Data protection and exploitation using *High Performance Computing (HPC)*
- *Reduce operator workload* by improving autonomy using hierarchical mission planning
- Improve *data flow and standard message architectures* for reliable communication

High Performance Computing Impacts

- Provides a *consolidated plug-and-play* application architecture
- Improves *scalability and feasibility* for unmanned aerial system vendors
- *Improved battle space awareness* via tasking, collection, processing, exploitation, and dissemination (TCPED) processes, required to translate vast quantities of sensor data into a shared understanding of the environment
- HPC enables *cross domain data sharing* of information and adapts rapidly to changing threats
- HPC addresses the challenges in *cloud computing* and *multilayer security*, communications, open standards, data storage, cost, ease of technology insertion, etc.

Ref: Unmanned Systems Integrated Road map FY 2013-2038 , Reference Number 14-S-0553

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